

## Landscape Modeling and Analysis Based on Digital Elevation Models Generated from Topographic Maps: Algorithm and Application on Safaga Area, Red Sea Coast, Egypt

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### Abstract

In this paper, we describe and demonstrate an efficient algorithm for DEM generation from scanned topographic maps. Further, we discuss the application of DEM for landscape modeling, spatial terrain analysis, extraction of the topographic parameters and features characterizing the modeled landscape. A set of FORTRAN programs were written to achieve this aim and the resulting outputs were incorporated into the GRASS GIS for further processing and 3-D visualization. Landscape modeling is an important step towards using raw topographic height data in GIS applications like landscape characterization, feature extraction, hydrological modeling, erosion and disaster damage prediction.

DEM helps in defining management zones based on the spatial variability of the topographic characteristics that affect to a great extent the properties of the surface covers and processes. Safaga area on the Red Sea Coast of Egypt was selected as the study area as it is characterized by hilly tracts bordering the coastal plain. The hilly areas experience torrential rains resulting in flash floods that cause serious environmental and human related problems in the coastal belt. Safaga area was selected in order to evaluate ways to mitigate flood related hazards on one hand and on the other hand, to perform geomorphic characterization of the terrain using GIS based techniques. This study is the first attempt towards building a comprehensive environmental database for the Red Sea Coast of Egypt and also a step towards 3-D representation of terrain features in the study area.

**Key-words** : DEM, Landscape modeling, Terrain analysis, GRASS GIS, Safaga Area, Red Sea Coast, Egypt.

### 1. Introduction

Digital Elevation Model (DEM) is a continuous representation of the surface topography, and as such, provides a base data set from which geomorphic parameters can be derived. The storage, display and analysis of data about the terrain surface are arguably one of the most widely used areas of GIS functionality. Digital

elevation models or DEMs are increasingly becoming the focus of attention within the larger realm of digital topographic data. Terrain is handled in GIS using DEM in which elevation values are estimated on a regular grid. This form of surface is the dominant of all of the earth's surface representation forms because the data structure of a grid shares much similarity with the file structure of digital computers, in that both afford the ability to store elevations as a two-dimensional array



(every point can be assigned to a row and a column). DEM allows modeling, analysis and the representation of topographic characteristics associated with the earth's surface.

The characteristics of the terrain—its elevation, gradient, aspect and curvature—have a variety of uses in geomorphometric applications (Pike, 1993) and in geomorphological and hydrological modeling (Moore *et al.*, 1991; Mitasova *et al.*, 1996). In addition, terrain morphology has a fundamental control on many aspects of environmental processes and also plays a significant role in controlling anthropogenic activities (Weibel and Heller 1991, Moore *et al.*, 1991).

Topography is a three-dimensional surface of complicated geometry and topology. Although land-surface form has been described successfully in rather general terms, Earth's terrain is much too varied and complex to be neatly categorized by most systems of classification (Evans, 1972). The best path to recognizing order in the face of such seeming chaos is to array the surface systematically, into nested components and describe them separately (Hammond, 1964). Such a hierarchical approach to spatial classification is a powerful method for investigating landforms defined by size, order, and geometric complexity (Dikau, *et al.* 1991 & Dikau, 1989).

In the present study, the extraction of terrain parameters is performed based on a suite of FORTRAN programs developed on the Open Source LINUX platform. The programs developed in the present study are closely integrated with GRASS (Geographic Resources Analysis Support System) Geographical Information System (GIS) package (USACERL, 1993; Byars and Clamons, 1997) in that they share a common data format. GRASS GIS is an open source, free raster based GIS with extensive support for topological vector format, image processing, and graphics production functionality. GRASS has ported to various operating systems and includes an easy-to-use Graphical User Interface (GUI), shell command interface and a robust graphics environment supported by X-Windows functions.

The main aims of this paper are to generate DEM from scanned topographic maps to model the landscape and to perform a spatial analysis of the topographic terrain. An attempt has also been made to derive the topographic parameters (slope, aspect, and curvatures) and the morphometric relief units (ridges, channels, and slope curvatures) characterizing the modeled landscape for Safaga area on the Red Sea Coast of Egypt. This is the first effort towards building a 3D database that

will allow decision makers in that area to manage the frequently occurring hazards, especially the geo-environmental problems related to torrential floods.

Digital terrain modeling and analysis encompasses the following general tasks:

- a) **DEM generation:** sampling of original terrain data and establishing topological relations for observations (model construction). DEM generation in this work is based on terrain elevation observations that are derived from four scanned topographic sheet maps of scale 1:50,000 (Egyptian Geological Survey, 1989), designated Safaga, Ras Abu Suma, Gabal Umm Inab and Gabal Wairah. The scanned images are subsequently edited and tagged with elevation values. The elevation matrix or rectangular grid is used to store and display the topographic surface, as it is the most commonly used modeling construct for a digital elevation models.
- b) **DEM manipulation:** modification and refinement of DEM and derivation of intermediate models and includes editing, filtering, merging and joining besides procedures for producing the final DEM.
- c) **DEM interpretation:** DEM analysis and information extraction from DEM. It serves to provide such geomorphological information through quantitative analysis of the digital terrain. Such analyses can provide direct input to a range of environmental and resource management applications. Interpretation may be directed at two different levels: (a) generation of slope and its dual derivatives of gradient and aspect in a general geomorphometric sense and (b) analytically portrays terrain features and attributes in relation to the surface hydrology at a more specific level. This is extremely useful in drainage basin delineation, hydrological run-off simulation as well as in geomorphological modeling studies.
- d) **DEM visualization:** graphical rendering of DEM and derived information. It plays a key role in facilitating the perceptual understanding and appreciation of terrain features. Visualization plays a major role in the interpretation and analysis of geomorphic features using graphical representations of the terrain.
- e) **DEM application:** development of appropriate application models for specific disciplines. It forms the context for digital terrain modeling: each application has its specific functional requirements relative to the other terrain modeling tasks and involves a vast array of environmental applications. Technological advances in computer graphics and visualization, spatial theory, databases, and a host of related areas is making it possible to explore, and apply DEM in var-



ied applications, such as civil engineering, earth sciences, planning and resource management, and logistics applications.

In the following sections, the study area is introduced and the algorithm for DEM generation from scanned topographic maps is briefly described. Further, the computational procedure for extracting topographic parameters and significant geomorphologic curvatures is explained. The results obtained using these computational procedures are presented and the characteristics of extracted geomorphic relief units are evaluated.

## 2. Study Area

The study area covers about 900 km<sup>2</sup> and is situated in the northern part of the Central Eastern Desert of Egypt. It represents the strip of the Red Sea Coastal Plain of Egypt extending from Ras Abu Soma bay in the north to Wadi Nuqara in the south, as well as the mountainous area till Gabal Ras Barud and Gabal Abu Furad to the west. The Red Sea Coastal Highway runs parallel to the Red Sea, while the Safaga-Qena Highway (160 Km) dissects the study area running west from Safaga City on the Red Sea Coast to Qena on the River Nile (Fig. 1).

The coastal plain forms a low land running paral-

lel to the general trend of the Red Sea and is covered by gravel and sand deposits with small low lying hills and hummocks (Fig. 2) ranging in age from Mesozoic, Tertiary to Quaternary. The basement rocks form the mountainous areas and consist mainly of Older Granites, together with a vast array of rock units comprising a metagabbro complex, Dokhan Volcanics, Young Gabbros, Younger Granites and post granite dyke suites (Fig. 3). Climate and verticality of mountains bordering the coastal plain in Safaga area are the principal causes of, as well as contributing factors to the flash

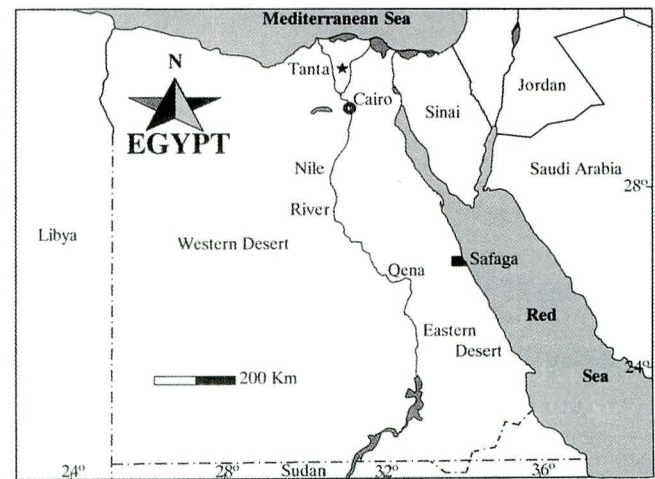


Fig. 1 Location map of the study area.



Fig. 2 Photograph showing the low lands and hummocks of the coastal plain (foreground) and the mountains (background) of Safaga area. Photo looking NW, Photographed by Masoud, Alaa, 12 Jan. 2001



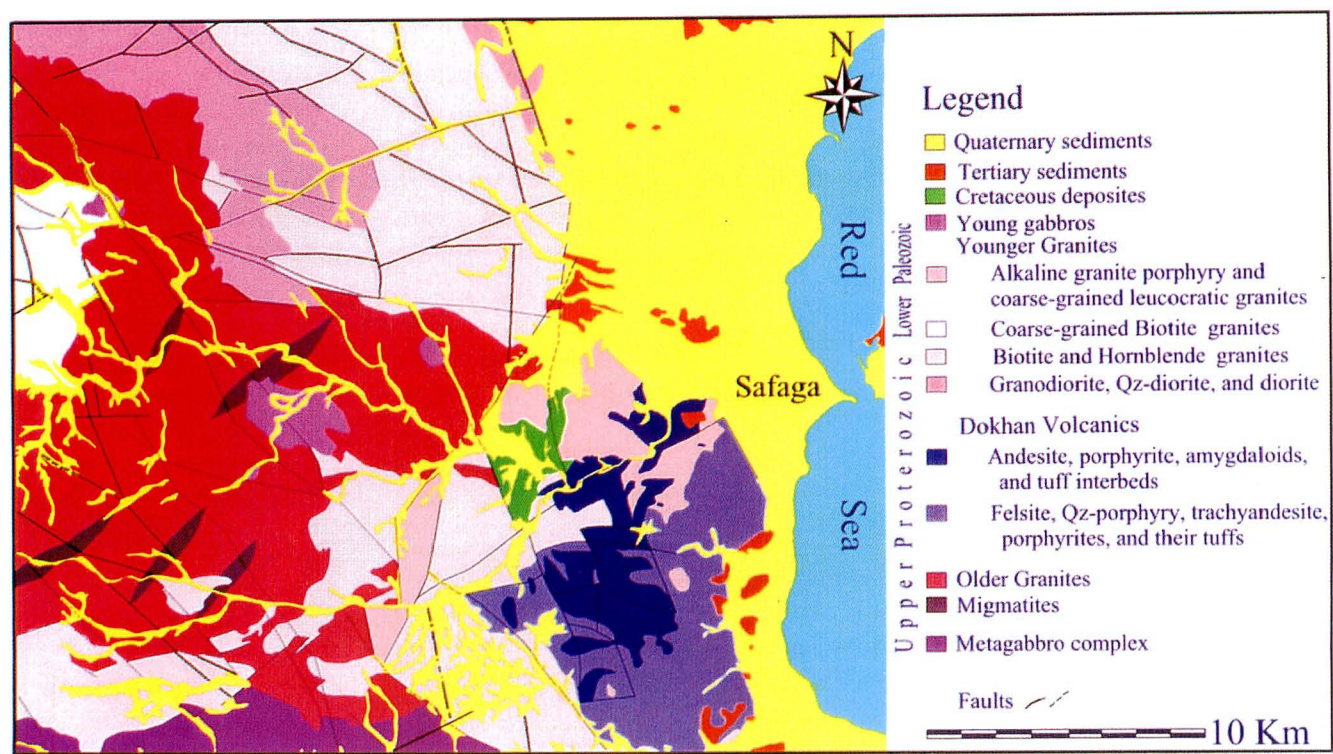


Fig. 3 Geology of the study area, modified after Egyptian Geological Survey and Mining Authority (1987) and Masoud (1997).

floods striking that area. The climate in the study area is arid, but some torrential floods may occur, reaching a maximum between November and January. This may cause serious problems and excessive loss of life and property.

3. Digital Elevation Model (DEM)

3.1 Background

A topographic map illustrates a dense distribution of inequality elevation information (Fig. 4) that enables the use of inter-contour data for the interpolation algorithm (Noumi et al., 1999). A point  $P(x_p, y_p)$  in the inter-contour area bounded by  $h_k$  and  $h_{k+1}$  contour lines gives an inequality constraints:

$f(x_p, y_p) - h_k > 0,$   
 $f(x_p, y_p) - h_{k+1} < 0,$   
 $f(x_p, y_p) - zh(k) = 0, \dots\dots\dots (1)$

where  $zh(k)$  is the spot height within the closure of a contour line.

A surface satisfying the constraints will generate a DEM consistent with the topographic map.

Global and local methods are the two main interpolation techniques, where the global uses all of the data values and aims at describing the general trend, whereas the local uses a limited number of values surrounding

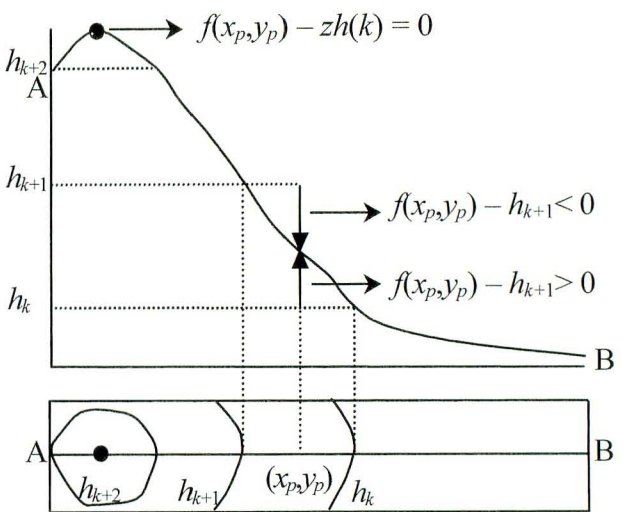


Fig. 4 Diagram showing constraints of the proposed interpolation algorithm.

a specific point in order to account for small-scale variations. The algorithm fits a smooth surface to data by minimizing the sum of squared residuals, iterating on the residuals using a penalty, and adding the data to the nearest grid point as the iteration proceeds. When processing topographic data, artifacts of natural variation and measurement errors may produce over-estimated or under-estimated elevations. Surface fitting by thin-



plate inserts a locally smoothed average instead of the strict surface. The smoothing generates an even surface, while still maintaining low residual values between the true points and the thin plate functions. The result is a preserved local variation in the terrain, but also smoothness without abnormalities.

### 3.2 Interpolation algorithm

The algorithm implemented in the Horizon program, a FORTRAN program written and revised from N88-BASIC program shown in Shiono *et al.* (1987), with a new gridding algorithm reported in Shiono *et al.* (2000), and the newly revised version in Shiono *et al.* (2001), enable the use of the inequality heights information extracted from scanned topographic maps to generate an optimized interpolated surface. The algorithm interpolates elevation data onto a grid through modest smoothing, the iteration works on least squared residuals at successively exterior penalty.

The basic principals of the interpolation algorithm are summarized in the following simple notations:

- (1) A surface  $f(x, y)$  is approximated by a set of values  $f_{ij}$  ( $i=1,..., Nx; j=1,..., Ny$ ) at each grid point.
- (2) Location of outcrop  $P(xh(k), yh(k), zh(k))$  provides equality and inequality constraints to the surface:

$$\begin{aligned} f(xh(k), yh(k)) - zh(k) &= 0 \\ \text{for } P \text{ on the surface} \\ f(xh(k), yh(k)) - zh(k) &> 0 \\ \text{for } P \text{ below the surface} \\ f(xh(k), yh(k)) - zh(k) &< 0 \\ \text{for } P \text{ above the surface} \end{aligned} \quad (2)$$

- (3) Surface determination is equivalent to a constrained optimization problem, i.e., to find the optimal solution  $f(x, y)$  such that objective function  $J$  (smoothness of the surface)

$$\begin{aligned} J(f) &= \\ \iint (\partial^2 f / \partial x^2)^2 + 2 (\partial^2 f / \partial x \partial y)^2 + (\partial^2 f / \partial y^2)^2 \\ dx dy \end{aligned} \quad (3)$$

becomes minimum subject to the proposed constraints.

- (4) The optimization problem is solved based on the exterior penalty method (Zangwill, 1967), in which

$$Q(f; a) = J(f) + a \phi(f) \quad (4)$$

becomes minimum, where  $\phi(f)$  represents the sum of

$$\begin{aligned} \sum [f(xh(k), yh(k)) - zh(k)]^2 / N' \\ \text{for } f(xh(k), yh(k)) - zh(k) = 0, \\ \sum [\max \{0, f(xh(k), yh(k)) - zh(k)\}]^2 / N' \\ \text{for } f(xh(k), yh(k)) - zh(k) < 0, \text{ and} \\ \sum [\min \{0, f(xh(k), yh(k)) - zh(k)\}]^2 / N' \\ \text{for } f(xh(k), yh(k)) - zh(k) > 0 \end{aligned} \quad (5)$$

$J(f)$  is the smoothness,  $a$  is a constant called a penalty and  $\phi(f)$  is the mean of squared residuals and  $N'$  is the number of data that does not satisfy the constraints. The optimal surface is a solution of linear simultaneous equation:

$$A u = b \quad (6)$$

defined by

$$\partial Q / \partial f_{ij} = 0 \quad (i=1,..., Nx; j=1,..., Ny)$$

where  $u = (f_{11}, f_{12}, ..., f_{Nx Ny})$

The penalty  $a$  starts from  $a_{Min}$  and increases exponentially to  $a_{Max}$ . The initial data values for the first  $a$  are calculated by summing the squared residuals of all of the data points that don't satisfy the optimization conditions based on the information of the inter-contour area with its surrounding contour heights, then the iteration works on a least squared residuals at successively increasing penalty until the maximum  $a$  is reached and a full estimation of the surface is acquired.

- (5) The simultaneous equations are solved by Choleski's method.

### 3.3 DEM generation steps

According to Noumi *et al.* (1999) algorithm, DEM was generated from scanned topographic maps based on the scale of 1:50,000. DEM generation was carried out using the Horizon program with the procedures shown on Figure 5.

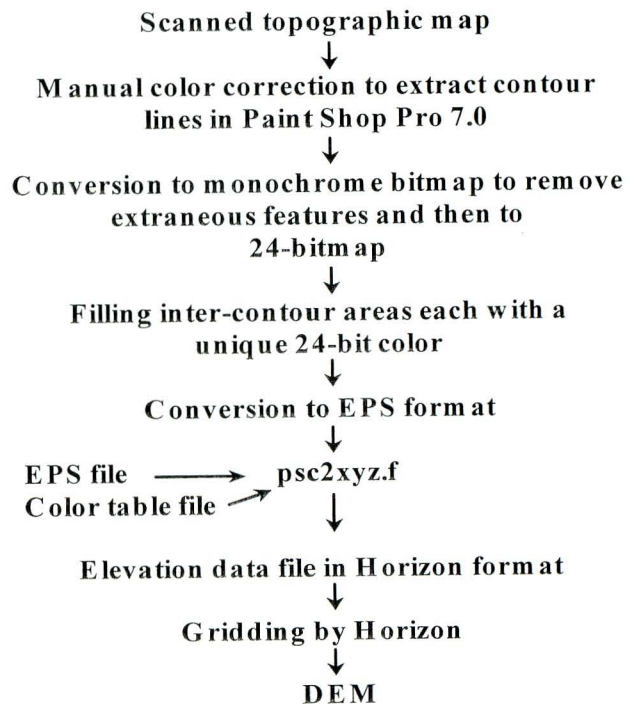


Fig. 5 DEM generation steps.



The first step in the creation of the DEM was to transfer the elevation information from the paper map we used into the Horizon program. This task would normally be accomplished through scanning of the original topographic map of the area of study. The map was first scanned into Paint Shop Pro 7.0 (Jasc Software, Inc., 2000) and touched up to remove all extraneous features (Fig. 6). Then the entire map was broken up into small rectangular sections with some overlap between each other. Each of these maps was transformed to a monochrome bitmap to extract only the contour lines, and then was converted to an encapsulated postscript image file format. Finally, a color table was prepared for each map assigning a unique value for each inter-contour area. Fig. 7 shows an example of a color table format with R, G, and B as the color components, pn is the button number assigned as 1 for point data in a closure of contour line, 2 for inter-contour area ranging in elevation from  $h_k$  (lower contour value) to  $h_{k+1}$  (upper contour value) and 3 for data below sea level (below zero contour value).

A psc2xyz.f, FORTRAN program is used to generate the XYZ data file from the postscript file together with the color table. This program is a new version of ps2xyz.f that was written to read 8-bit image files by Noumi *et al.* (1999), modified to read 24-bit colored postscript maps to adapt with the large number of colors required to cover the large area accessed and the high rate of change in elevation in the area of study. Table 1 shows an example of XYZ data format, where lm is the elevation constraints, as +1 means that the surface must pass above this point, 0 means that the surface must pass through this point, and -1 means that the surface must pass below this point. The Horizon

program reads in the XYZ data to estimate the surface and finally to build the landscape model through  $\alpha$  parameter that optimizes the surface estimation. The output of the Horizon program is an ASCII file that makes the output compatible with the other GIS packages to read and process through it. In our area of study, the most promising value for maximum  $\alpha$  was  $10^4$ , where  $\alpha$  starts at 0.1 and increases exponentially at a ratio of 1.2; higher  $\alpha$  values may result in over/under-estimation of the surface, particularly where the rate of change in the terrain elevation is relatively high, while lower values for maximum  $\alpha$  adds some smoothing to the interpolated surface. Fig. 8 shows the effect of the  $\alpha$  parameter on the interpolated surface.

The resulted DEMs are patched together to build the whole DEM that is subsequently edited and filtered to remove the errors resulting from the patching process, and to produce the final DEM of the study area with a mesh size of 28.5 m. The final DEM is good enough to simulate the original topographic map (Figs. 9 and 10).

Table 1 Example of the Horizon input file format.

X	Y	Z	lm
50	50	90	0
50	50	90	-1
240	130	80	-1
240	130	60	+1
~	~	~	~
370	220	20	-1
370	220	0	+1
370	221	0	-1
9e+09	9e+09	9e+09	9e+09

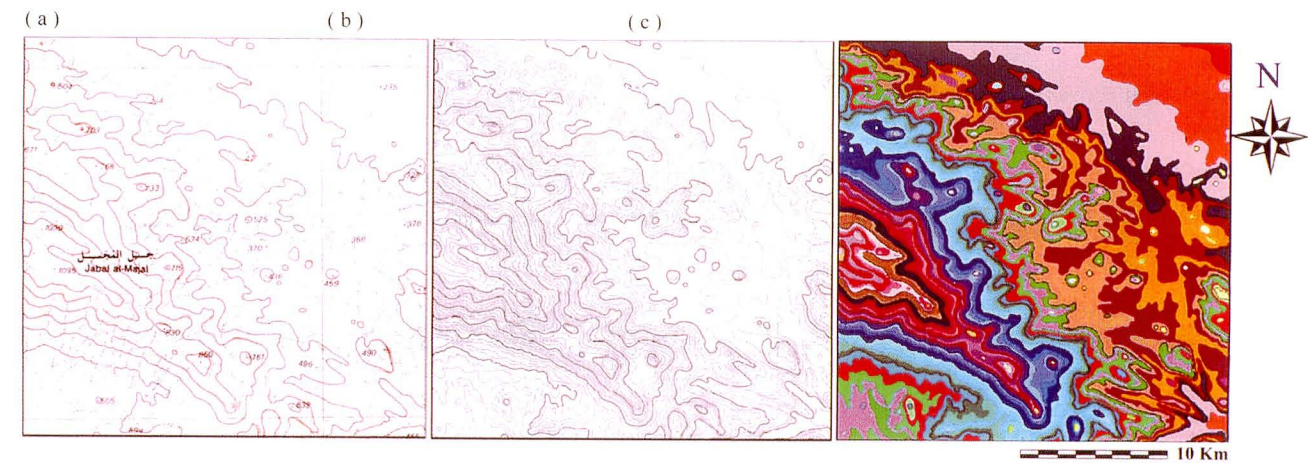


Fig. 6 Test data processing: a) Original topographic map, b) Extracted contour lines, and c) Inter-contour areas filled with unique 24-bit colors.



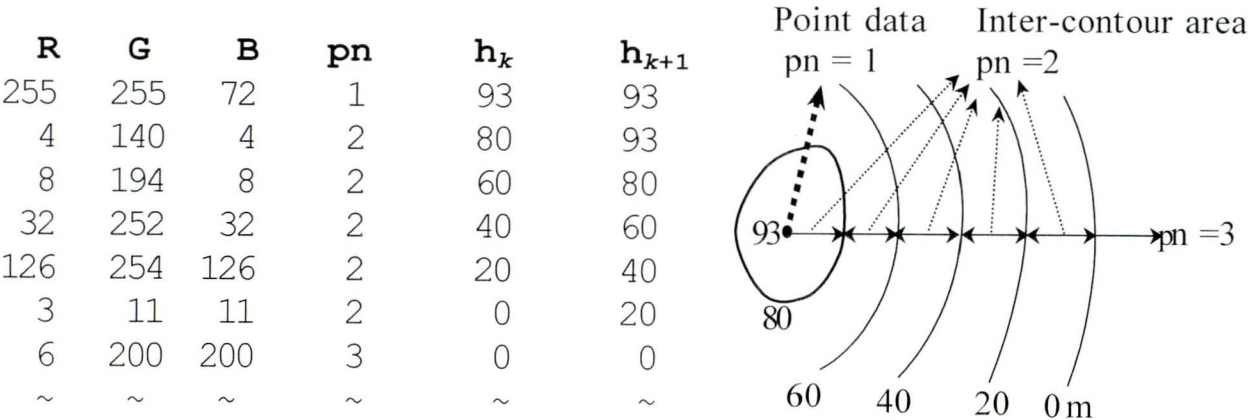


Fig. 7 Example of a color table format with illustrations.

4. Terrain analysis

4.1. Derivation of morphometric parameters

TerrAna.f, a Terrain Analysis FORTRAN program was written and used to derive the terrain attributes. Terrain attributes can be separated into primary and secondary attributes. Primary terrain attributes were directly calculated from elevation data and include first and second derivatives such as slope, aspect, profile curvature, plan curvature and tangential curvature and can be derived by moving 3 x 3 submatrix over the DEM (Fig. 11).

In order to derive the mathematical expressions for terrain attributes, the following simplified notations are used:

$$\begin{aligned} f_x &= \partial f / \partial x, & f_y &= \partial f / \partial y, \\ f_{xx} &= \partial^2 f / \partial x^2, & f_{yy} &= \partial^2 f / \partial y^2, & f_{xy} &= \partial^2 f / \partial x \partial y \end{aligned} \tag{7}$$

Where z is the elevation, x and y are the axes in the horizontal plan, and

$$\begin{aligned} P &= f_x^2 + f_y^2, \\ Q &= P + 1. \end{aligned} \tag{8}$$

Central finite difference forms of the partial derivatives for the central node can be written as:

$$\begin{aligned} f_x(x_i, y_j) &= (f_{i+1,j} - f_{i-1,j}) / 2dx, \\ f_y(x_i, y_j) &= (f_{i,j+1} - f_{i,j-1}) / 2dy, \\ f_{xx}(x_i, y_j) &= (f_{i+1,j} - 2f_{i,j} + f_{i-1,j}) / dx^2, \\ f_{yy}(x_i, y_j) &= (f_{i,j+1} - 2f_{i,j} + f_{i,j-1}) / dy^2, \text{ and} \\ f_{xy}(x_i, y_j) &= (f_{i+1,j+1} - f_{i-1,j+1} - f_{i+1,j-1} + f_{i-1,j-1}) / 4dxdy. \end{aligned} \tag{9}$$

where dx and dy are the grid spacing in x and y directions, respectively. The topographic attributes are calculated using the following relationships:

$$\begin{aligned} \text{Slope } (\theta) &= \arctan [(f_x^2 + f_y^2)^{1/2}], \\ \text{Aspect } (\phi) &= \arctan (-f_x / -f_y) \end{aligned}$$

where  $\phi = 0$  in north direction.....(10)

Profile Curvature  
$$= (f_{xx} f_x^2 + 2f_{xy} f_x f_y + f_{yy} f_y^2) / PQ^{3/2} \tag{11}$$

Plan Curvature  
$$= (f_{xx} f_y^2 - 2f_{xy} f_x f_y + f_{yy} f_x^2) / P^{3/2} \tag{12}$$

Tangential Curvature  
$$= (f_{xx} f_y^2 - 2f_{xy} f_x f_y + f_{yy} f_x^2) / PQ^{1/2} \tag{13}$$

The topographic curvatures are calculated using the methods reported in Mitsova and Hofierka (1993).

Fig. 12 (a and b) shows the slope and the slope classes for the study area. The slope or gradient is the central, and often the most frequently applied parameter according to a morphographic relief description. The slope is deduced from the angle oriented in the slope direction between a horizontal plane and the slope area, mostly indicated in degrees, more rarely in percentage. It influences flow rates of water and sediment by controlling the rate of energy expenditure or stream power available to drive the flow. It affects the velocity of both surface and subsurface flow and hence erosion potential, soil formation, long-term average soil water content and many other important surface processes and properties.

Fig. 12 (c and d) shows the aspect and the aspect classes for the area under consideration. The aspect or exposure represents a further essential, and frequently applied, morphometric parameter. Aspect describes the direction of the strongest slope grades and results from the projection of the direction of gradient onto the horizontal plane. The aspect will specify an angular degree clockwise from the geographic north. It influences the direction of water flow.

Topographic curvature has its control influence on the slope drainage as an essential factor of the slope dynamics, and as a further essential relief feature. Curvatures are based on second derivatives-the rate of



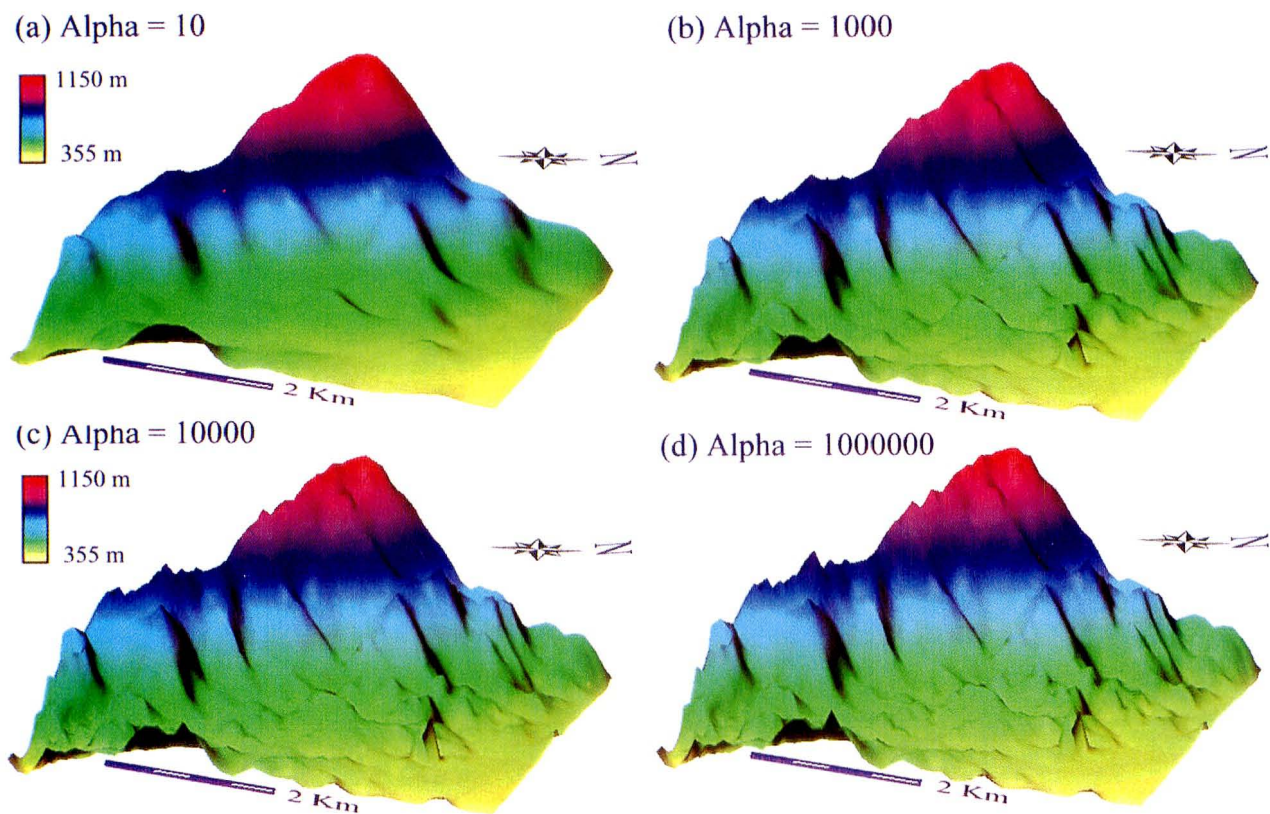


Fig. 8 Test data DEM produced from the Horizon program with different max.  $\alpha$  parameters: a)  $\alpha=10$ , b)  $\alpha=1000$ , c)  $\alpha=10000$ , and d)  $\alpha=1000000$ .

change of a first derivative such as slope or aspect, usually in a particular direction. Curvatures have a sign that represents whether a surface is convex or concave. The standard sign convention is positive values for convex curvature and negative values for concave curvature. There are many curvatures for the surface depending on the plane in which curvature is calculated; here we are concerned with the profile, plan and tangential curvatures (Fig. 13).

Profile curvature calculates the curvature perpendicular to the elevation contours (rate of change of slope along a flow line) from DEMs, which indicates whether any particular point on the hillslope profile is in an area of convex or concave curvature. This indicates whether the flow upon this area is more likely to be fast or slow, within the study area, it ranges from 1.706 to -1.432 and is classified as convex (positive values), concave (negative values) and plane (zero curvature). Fig. 13 (a and b) shows the profile curvature and its classes within the study area.

Plan curvature calculates the curvature of slope that is parallel to the elevation contours (rate of change of aspect along a contour) which can be used to help identify divergent or convergent flow areas on the land-

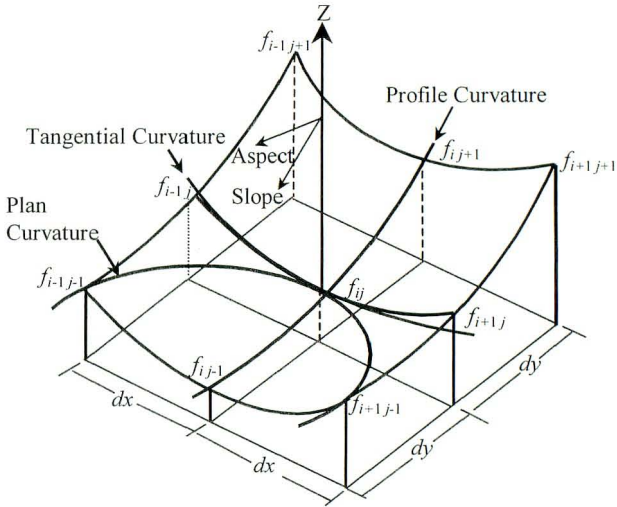


Fig. 11 3 x 3 submatrix upon which the topographic attributes are calculated.

scape: convergent flow generally indicates higher erosion and transport potential, while the divergent flow indicates lower potential. Fig. 13 (c and d) shows the plan curvature and its classes. Plan curvature of the study area ranges from 320 to -326 and is classified as convex, concave and plane curvature.



Tangential curvature calculates the curvature of a normal plane section in a direction perpendicular to gradient (direction of tangent to the contour line) and can be used also to help in identifying divergent or convergent flow areas on the landscape. Fig. 13 (e and f) shows the tangent curvature and its classes. Tangent curvature ranges from 2.75 to -2.28 and is categorized as convex, concave and plane curvature.

#### 4.2 Landscape classification

Landscape units can be characterized by their geomorphic form. These forms are defined by their slope curvatures (profile and plan curvatures). Curvature of slope can be convex, flat, or concave and it determines the speed and flow of water over the surface. The proposed algorithm is based on the fact that any part of the terrain which is locally concave-upward will be a channel or part of it where surface runoff will tend to be concentrated, while convex-upward cells will be a ridge or part of it where surface runoff will tend to diverge. A 3x3 window can be moved over the DEM to identify upwardly concave and convex areas. Cells that represent the concave-upward areas are assigned to be part of the stream or channel network, while those that are convex-upward are assigned to be part of the ridge.

After the derivation of the morphometric parameters, curvature of slope based on the positive and negative values of profile and plan curvature are used to define the basic morphometric forms. Profile curvature is the curvature of the slope. Convex profile curvatures indicate areas of accelerated flow, while concave profile curvatures indicate areas with decreasing flow. Plan curvature is the curvature along the contour. Convex plan curvatures represent areas of divergent flow, while concave plan curvatures represent areas of convergent flow. So, an area that has a convex plan curvature is typical of a ridge. The flow of water over this form would be divergent. An area that has a concave plan curvature is typical of a channel. The flow of water over this form would be convergent. Where the plan curvature is zero, profile curvature is used to define the slope curvature; a convex profile curvature represents a convex slope unit, a concave profile curvature represents a concave slope unit, and a plan slope units occur where the profile curvature is zero. Channels, ridges, and slope curvatures are derived and mapped based on the proposed classification scheme. Fig. 14 shows the extracted landscape classes and its shaded relief map. Fig. 15 shows the extracted ridges, channels and the slope curvatures and their corresponding shaded relief maps and the classification scheme upon which the land-

scape units are classified. Relief shading enhances the digital topographic data and thematic maps to appear to have three-dimensional aspects; this is a widely used technique within many of the GIS packages.

As the DEM has a resolution of 28.5 m, and the filters are 3 x 3 submatrix, only relative curvature within 57 x 57 m is calculated. However, the more precise resolution of the DEM may yield more differentiation of results and a significant increase in the amount of data, as well as in the calculation expense. Table 2 shows the spatial distribution of the landscape classes in relation to the slope.

It was observed that bedrock structural features have exerted a strong influence on channel patterns in the area of study. Straight, continuous stream valleys, discontinuous valley segments, or en echelon stream valleys define the major lineaments that correspond to well-known surficial joint sets; these, in turn, give the appearance of being related to deep-seated faults that needs detailed further investigations.

#### 5. Summary and conclusions

Digital elevation modeling has the potential of accurately defining the spatial variability and complexity of actual terrain surfaces. A new surface modeling technique was introduced that facilitates a more accurate and reliable basis for realistically modeling the landscape. Minimization of discretisation error has been successfully implemented and has yielded a useful criterion for optimization of the generated DEM with information contained in the raw source data. The DEM (with a mesh size of 28.5 m) was generated from scanned topographic maps based on the scale of 1:50,000. This ground resolution was selected to perform further analysis using Landsat TM remote sensing data covering the area of study. Regarding the accuracy of the DEM at this resolution, there is no other accurate source data to correlate with on one hand and 28.5 m mesh size from 1:50,000 topographic maps with a contour interval of 10 m in coastal flat areas and 20 m in mountainous areas is good enough to represent the landscape on the other hand. From this DEM, the most important morphometric parameters (slope, aspect, profile curvature, plan curvature, and tangential curvatures) were derived and terrain classification was carried out.

A landscape classification procedure was developed which was based on the generated DEM. It was possible to classify the landscape of the study area, based on the terrain curvature, into five different landscape elements; ridges, channels, convex slope, concave slope



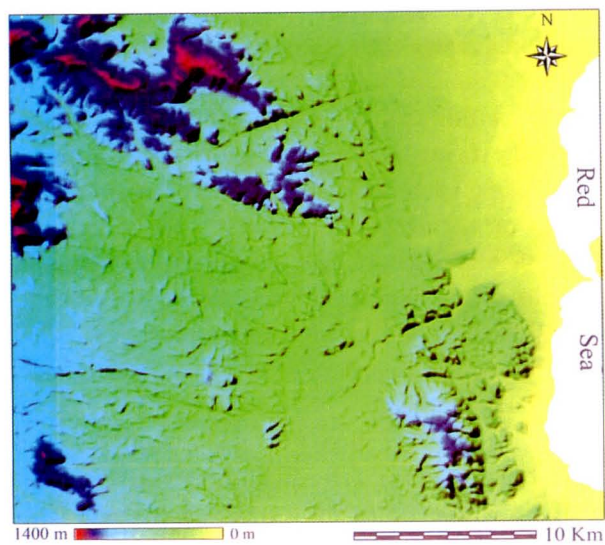


Fig. 9 Digital Elevation Model of Safaga area.

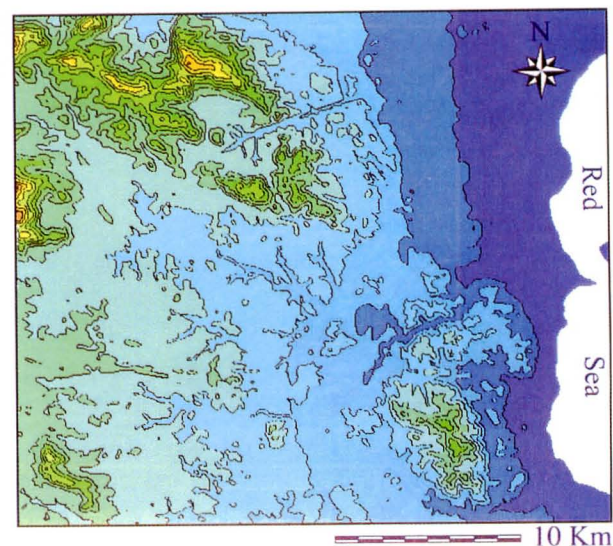


Fig. 10 Digital Elevation Model (DEM) with contour lines of Safaga area. Contour Interval 100 m.

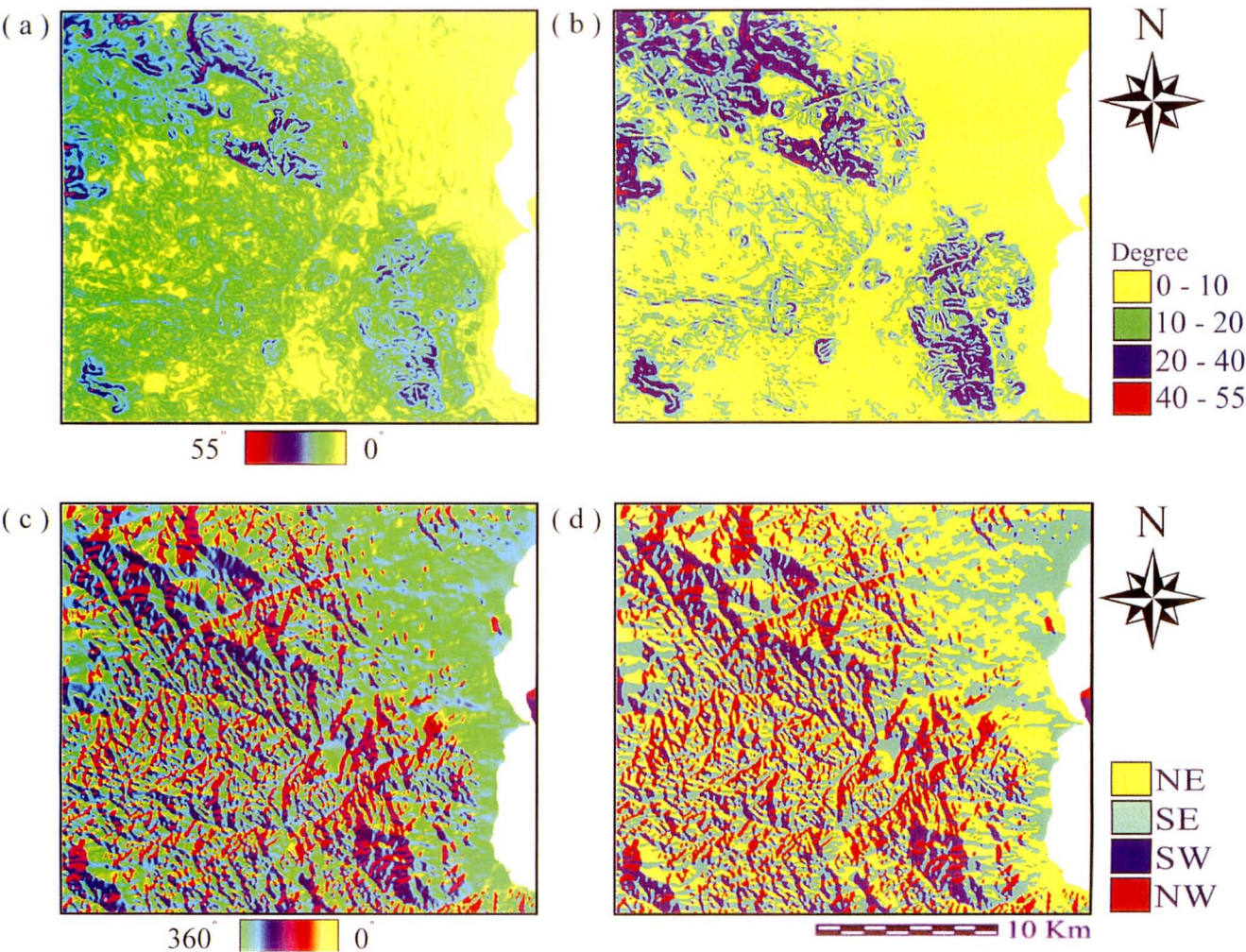


Fig. 12 Primary terrain derivatives: a) slope, b) slope classes, c) aspect, clockwise from North, and d) aspect classes.



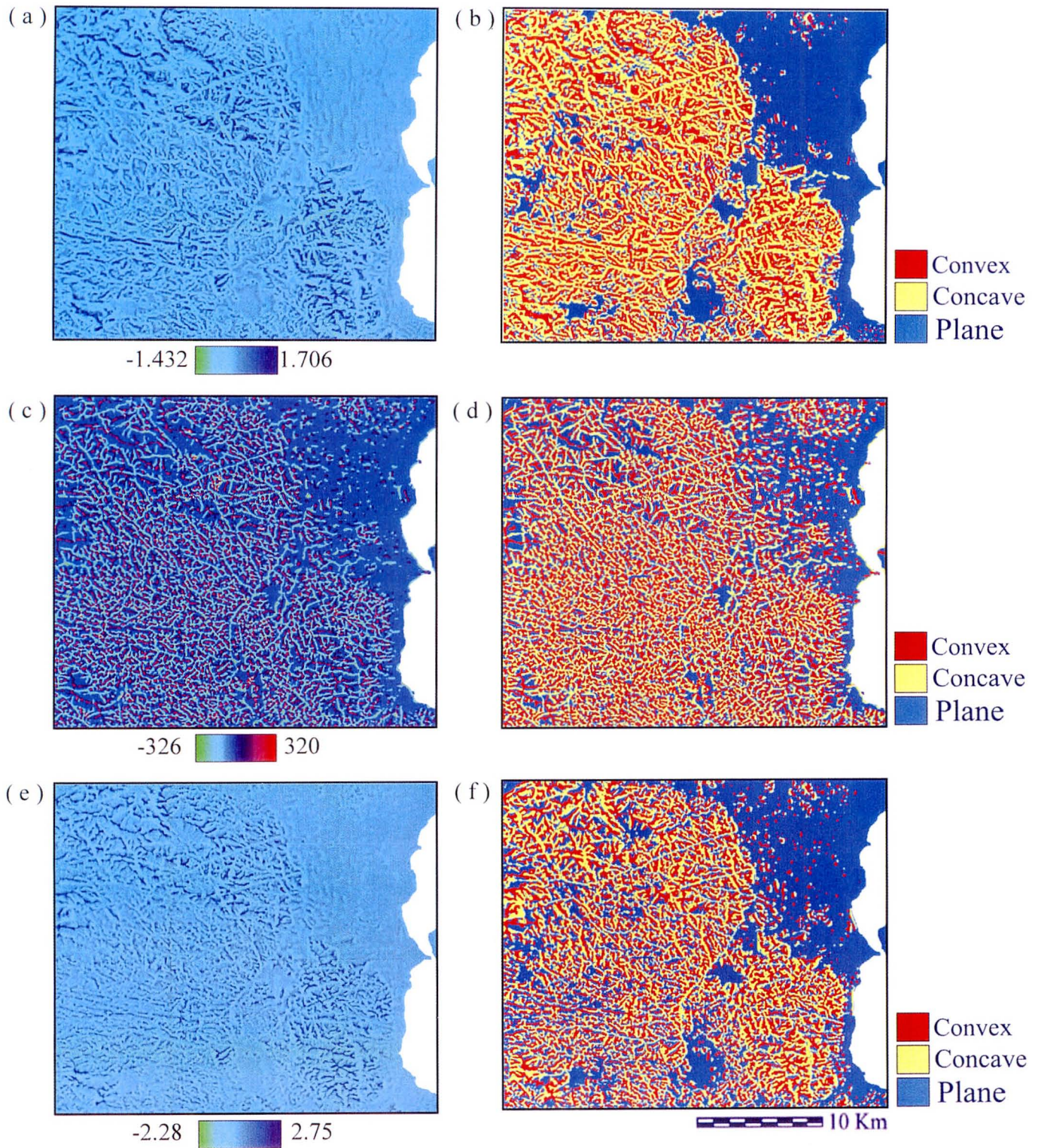


Fig. 13 Topographic curvatures: a) profile curvature, b) profile curvature classes, c) plan curvatures, d) plan curvatures classes, e) tangential curvatures, and f) tangential curvatures classes.



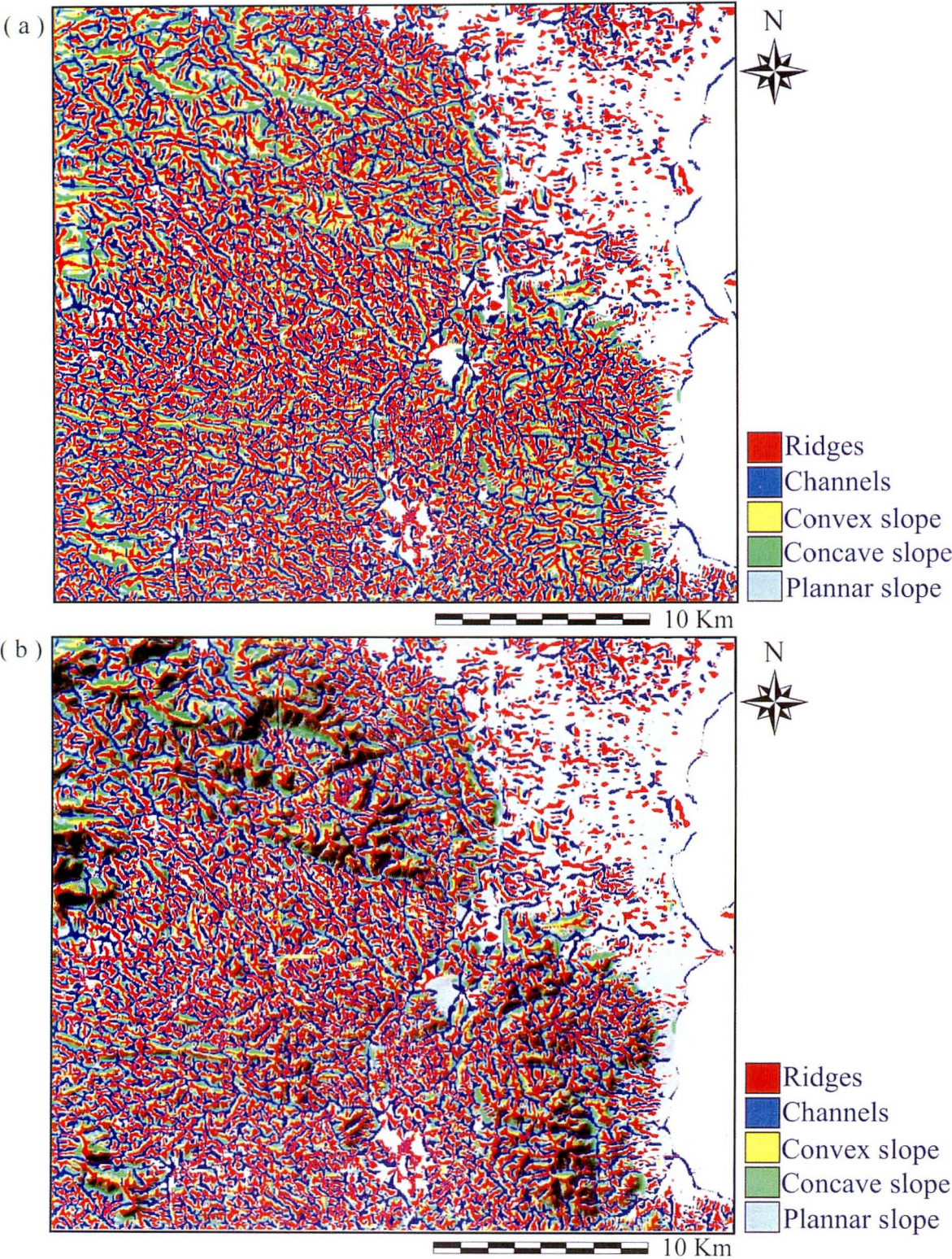


Fig. 14 Landscape classes of Safaga area: a) 2D classes, and b) shaded relief classes.



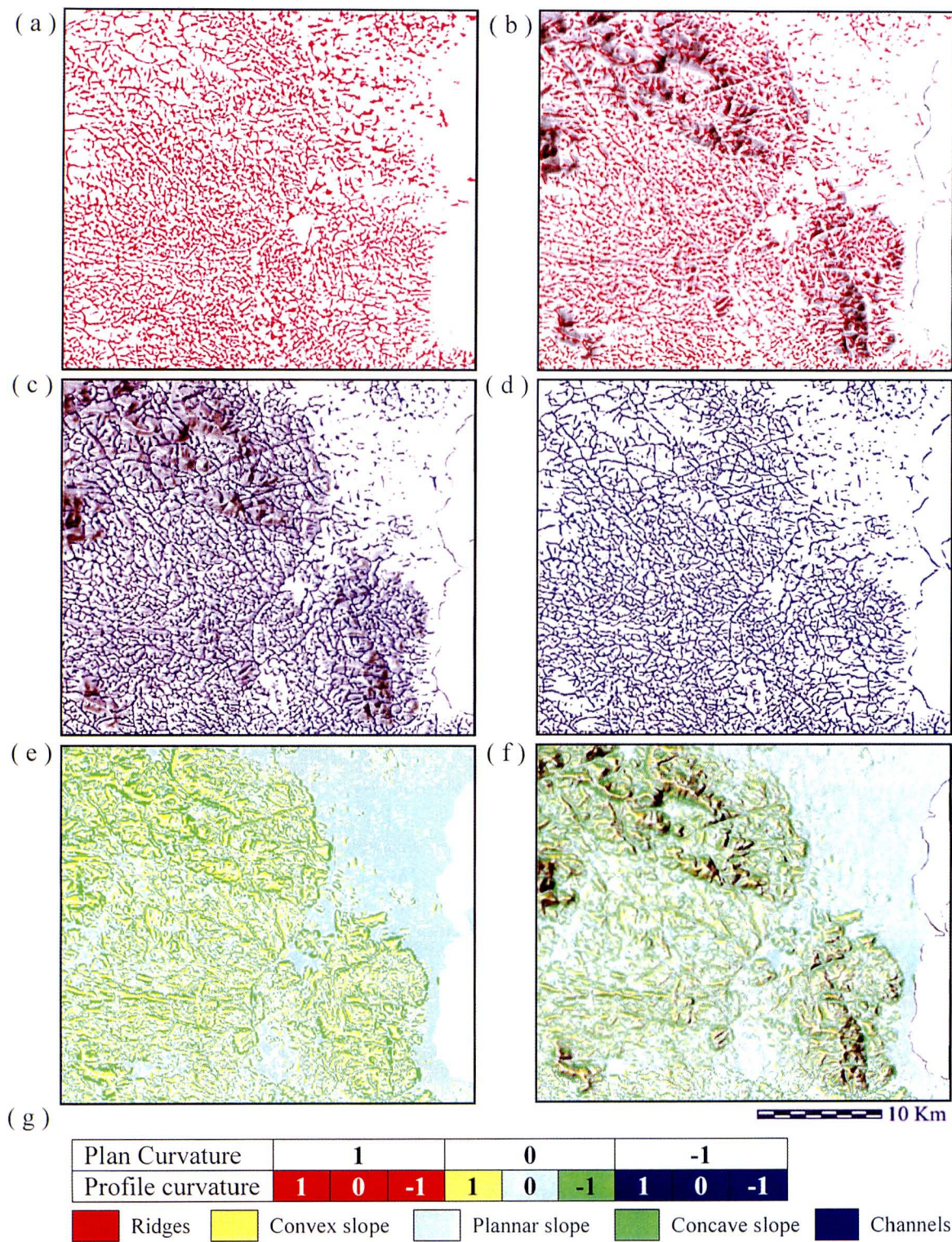


Fig. 15 Landscape morphometric relief units and classification scheme: a) ridges, b) shaded relief ridges, c) channels, d) shaded relief channels, e) slope curvature, f) shaded relief slope curvatures, and g) classification scheme.



and planar slope characterizing the landscape of the study area. Safaga area was selected in order to evaluate ways to mitigate flash flood related hazards as well as to perform geomorphic characterization of the terrain using GIS based techniques.

Detailed terrain model at 28.5 meter spacing have proved effective in describing the morphometric parameters and relief units for the study area. Such a 28.5-meter grid might well prove important in future geomorphometric work in the Red Sea hills, and would be a useful input in mitigating the natural hazards that may threaten the future of this area. The landscape classification model adopted in the present study has good potential to aid in understanding the surface processes affecting the topographic forms. The landscape maps should not be used to map the geomorphic forms only, but they may be useful as decision-support for geo-environmental assessments. This study is the first attempt towards building a comprehensive environmental database for the Red Sea Coast of Egypt and also a step towards 3-D representation of terrain features in the study area.

Beside the positive results of this work, some starting points can be found for further improvement of the morphometric and morphographic relief analysis. For the terrain classification on the micro-scale, connection between DEM data and high-resolution multi-spectral satellite data would allow more detailed segmentation of the geomorphic and landuse units. Finer resolution DEM would also be useful in carrying out texture analysis that would provide useful clues for correlating surface characteristics with geological materials.

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